PentaVac™ Vacuum Technology

Scientific CCD Applications

CCD imaging sensors are used extensively in high-end imaging applications, enabling acquisition of quantitative images with both high (spatial) resolution and high sensitivity. Applications such as high content screening, genome sequencing, FRET / FRAP / TIRF, to name but a few, utilize the highest performance imaging devices available. Multi-mega pixel sensors are available with peak quantum efficiencies (QE) approaching 100% and a read noise floor of 2 electrons rms or less, presenting the user with an extremely sensitive imaging device. However there are some photon-starved applications, including bio-luminescence, astronomy and fluorescence microscopy, which require even these highly sensitive devices to be used with both long integration (exposure) times and high amounts of binning (on-chip charge summation) in order to obtain a detectable signal. For these type of applications the CCD sensor must be deep cooled in order to reduce the noise component associated with dark signal.

What is PentaVac™ Technology?

PentaVac™ Technology capitalizes on Raptor Photonics years of experience and expertise in scientific camera design to provide a rugged, compact, high performance, deep cooled camera platform, suitable for the most demanding scientific applications. PentaVac™ comprises:

1) A truly hermetic, compact, rugged sensor enclosure – free from the leak paths and fragility associated with 'quasi-hermetic', epoxy sealed enclosures.
2) Lifetime vacuum guarantee - made possible by careful material selection and extensive cleaning and material treatment, minimizing outgassing and virtual leaks.
3) Gettering – multistage gettering to preserve the vacuum environment around the sensor for the lifetime of the camera, even under harsh operating and storage conditions.
4) High performance multistage ThermoElectric Coolers (TEC) – enabling deep cooling of a range of sensor formats (achieving temperature differences in excess of 110°C) with high reliability and maintenance free operation.
5) Low thermal resistance between TEC and cooling medium – thermal design of sensor enclosure and camera components minimizes both the heatload presented to the TEC and the temperature drop between the TEC hotside and cooling medium. This maximizes the cooling performance whilst minimizing the power requirement of the camera system.

PentaVac™ Technology is available for a range of sensor types and formats, with a range of TECs and cooling methods which can be tailored for specific application requirements.

Why are CCD Sensors Cooled?

The obvious answer is to improve the quality of the image produced by the camera / imaging system. Simply by comparing the two images in Figure 1 below, one can qualitatively see the image quality improvement produced by cooling the CCD sensor. The reduction of two main effects have caused this observable improvement in image quality:

1) the dark signal per individual pixel
2) the impact of hot pixel (defects) within the sensor array

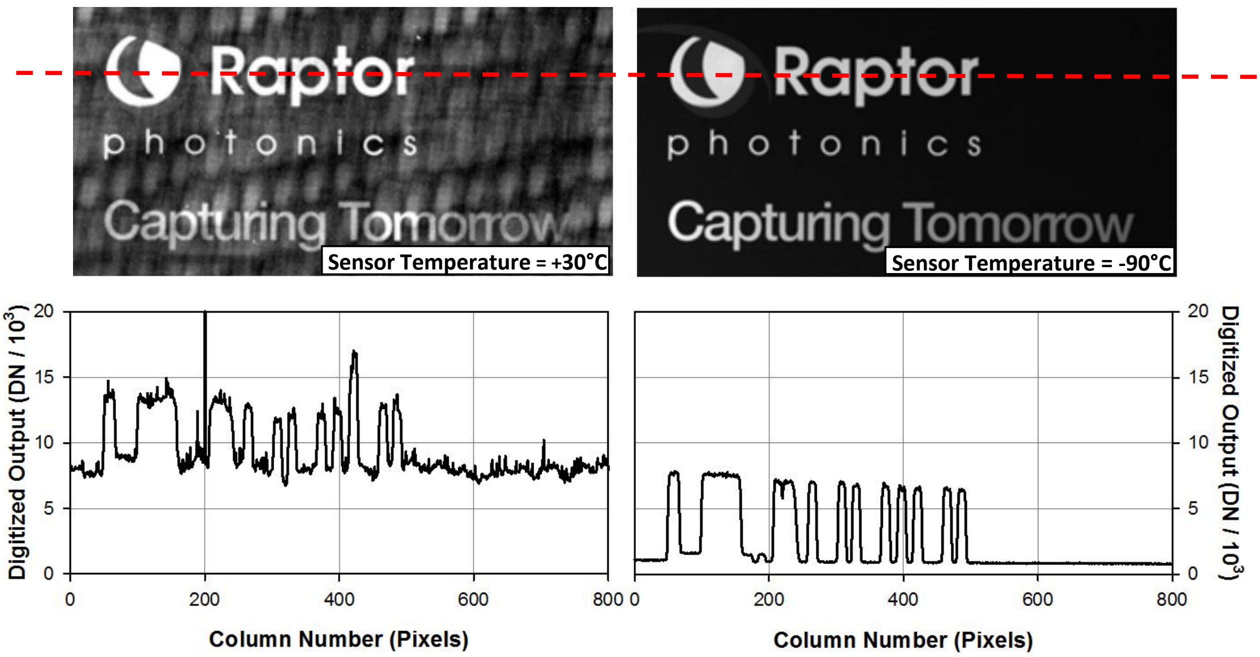

Figure 1: Sample images demonstrating the image quality improvement due to cooling the CCD sensor. Both images acquired using the same lens configuration and exposure time (10seconds). Section plots are shown through both images at the location of the dashed line.

Effect of Cooling on CCD Images

Dark Signal

The dark signal (as the name suggests) is a signal generated within the sensor even when zero photons are incident upon it. Thermal excitation of electrons from the valence band into the conduction band produces a charge which is stored within the pixels of the CCD sensor. These thermally generated electrons are indistinguishable from photoelectrons produced by the absorption of photons within the sensor. Therefore the output from each pixel of the device contains electrons produced by thermal excitation in addition to those generated by the photons that you are actually trying to detect / measure. It is common for the rate of generation of dark signal to be described as a dark current, usually in units of electrons per pixel per second (i.e. charge per unit area per unit time), averaged over the area of the sensor. This can allow the user to estimate how significant the dark signal will be for their specific acquisition conditions (i.e. exposure time, CCD temperature, binning configuration). High-end CCD sensor manufacturers already invest significant time and effort in their pixel designs to ensure that their devices exhibit low dark current. This can involve inserting dopants within the depletion layer of the CCD enabling the device to be operated in MPP-mode (Multi Pinned Phase mode), also known as IMO (Inverted Mode Operation). Appropriate biasing of these devices can reduce the dark current by up to two orders of magnitude, however even then many applications require a further reduction in dark current, which is typically achieved by cooling the sensor.

Hot Pixels

Hot pixels within a device are basically pixels which have a dark current much higher than the mean dark current of the device. They manifest as bright speckles / spikes within the image, as can be seen in the left-hand image and section plot of Figure 1. Deep cooling the CCD sensor can also reduce their impact to negligible levels, resulting in a ‘cleaner’ image and increasing the percentage of the sensor array which can produce valid data when using long exposures.

Comparing dark images for two different sensor temperatures, see Figure 2, can also illustrate the benefits of cooling the CCD sensor.

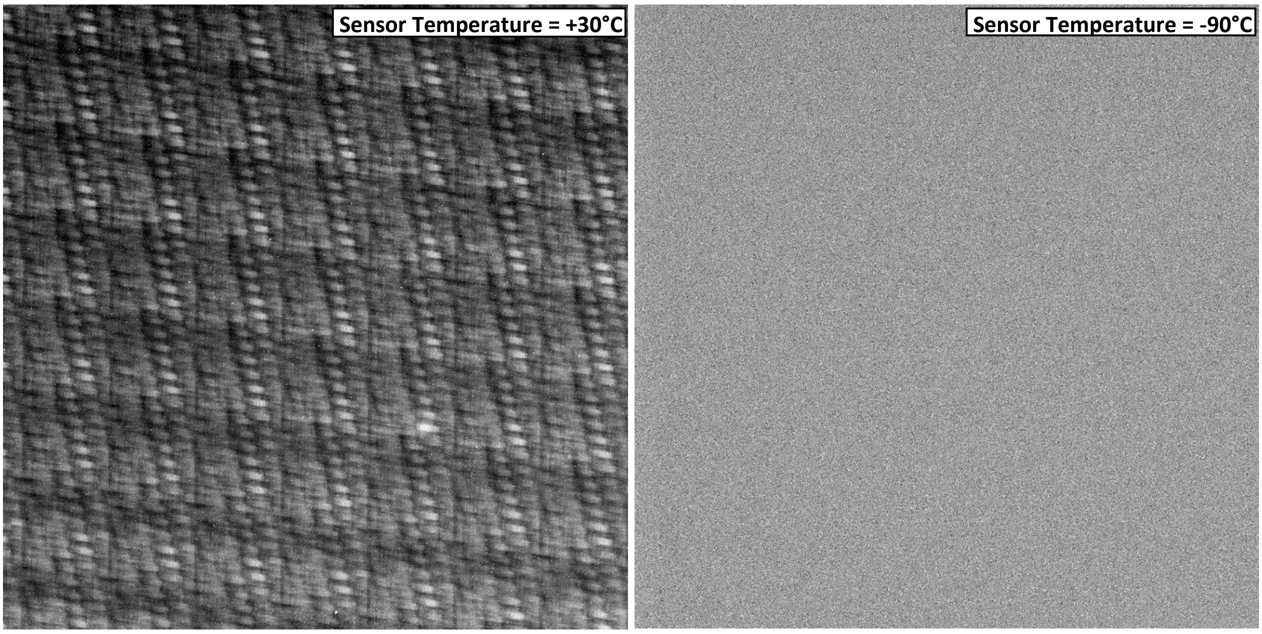

Figure 2: Sample 10 second exposure dark images highlighting the reduction in dark signal and hot spots due to cooling the CCD sensor. The only acquisition parameter changed is the CCD temperature.

The image taken at +30°C exhibits a significant number of hot pixels and a well-defined structure, due to dark current non-uniformities introduced by processing of the sensor during fabrication. Acquiring the same image, using the same sensor, but cooled to -90°C results in an image which has an extremely flat, featureless appearance with only white noise present.

This is perhaps even more apparent by comparing cross-sections through the center of each image, as shown in Figure 3. (Note the scale in the upper section of the graph is two orders of magnitude larger than that of the lower section).

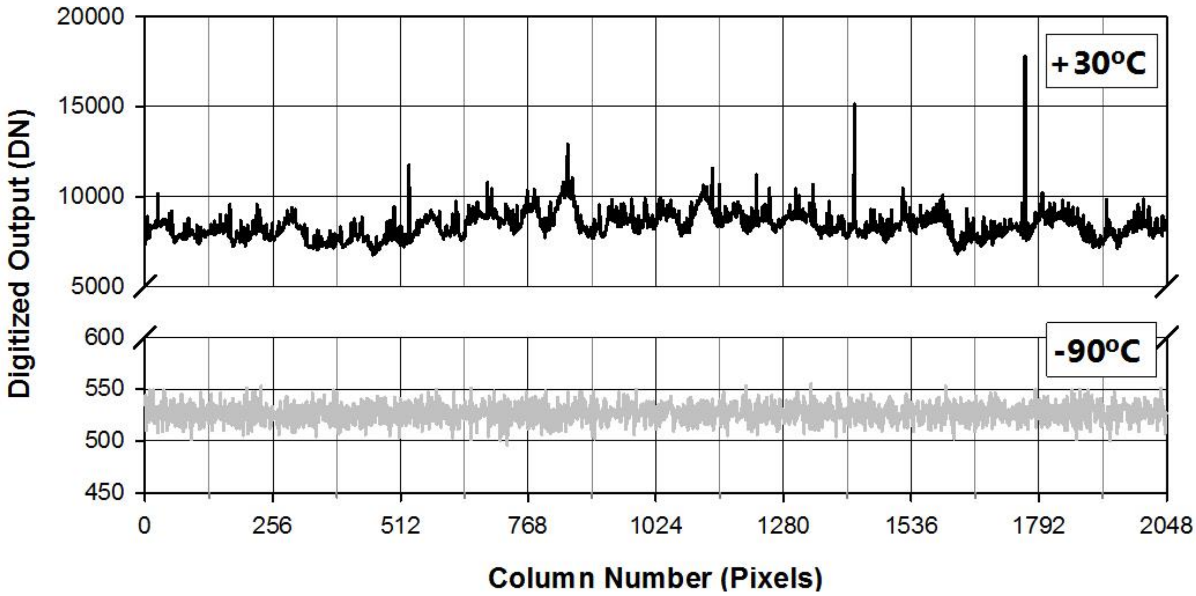

Figure 3: Line profiles of the central row of two, 10 second exposure, dark frames. The only acquisition parameter changed is the CCD temperature. **Note** the difference in vertical scale between the top and bottom section of the graph.

Plotting histograms of the dark images, Figure 4, also provides a more quantitative measure of the improvement.

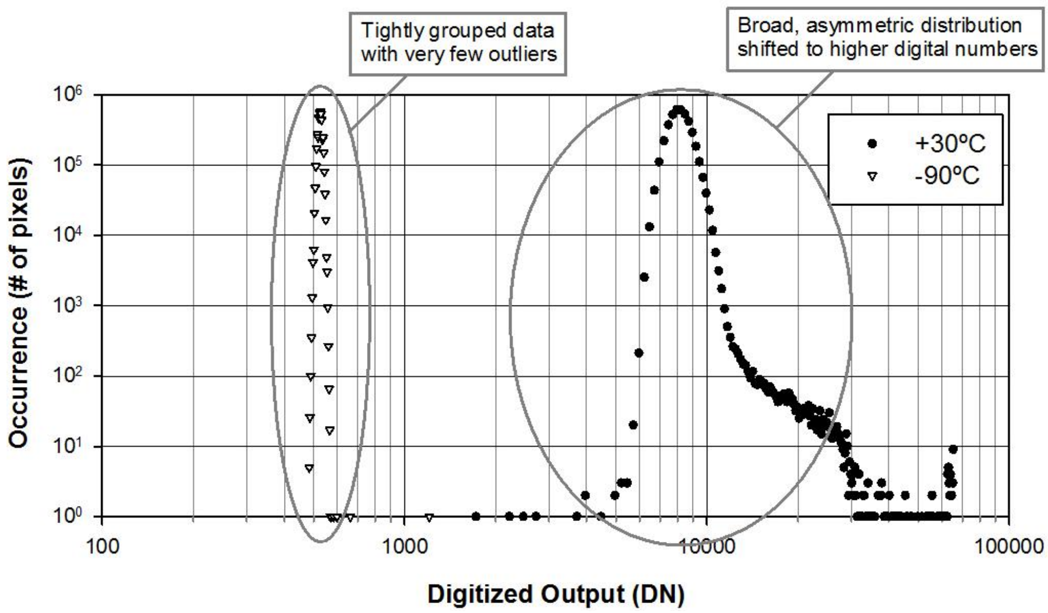

Figure 4: Histograms of two, 10 second exposure, dark images acquired at different CCD temperatures.

The distribution for the image acquired at +30°C shows a distribution located at relatively high (several thousand) digital numbers (DN) and has a clearly defined tail towards higher DN. Note that there are already an appreciable number of pixels at or close to saturation, even in complete darkness! In contrast the distribution for the image acquired at -90°C shows a tightly grouped, normal distribution, centered at low digital numbers, with very few outliers.

Residual Image

All CCD sensors contain defects and imperfections within the silicon wafers used for their fabrication. These defects can temporarily hold some charge (including photo-generated charge) and have a release rate which is temperature dependent. At colder CCD temperatures the amount of trapped charge released per unit time is less (for a given sensor) than at warmer temperatures.

Under many standard acquisition conditions, the capture and release of this charge has little or no detrimental effect on acquired images. One exception occurs in applications which involve acquiring a 'bright' image, immediately followed by acquisition of a long, dark image with high binning, in order to detect a much weaker signal. The bright image can result in a large number of the defect sites being filled with charge. During the subsequent long exposure this residual charge is released, some of which is collected within the potential wells of the CCD pixels. A 'ghost' image is observed when the collected residual charge is sufficiently large to be distinguished above the noise floor. The use of binning, sums the residual charge within the binned pixels making it more likely to be discernable above the noise floor. As mentioned above, deep cooling a CCD to -90C 'freezes' the charge into the defect sites, so for a given integration time the amount of charge released (and collected in the pixels) appears reduced when compared to an image acquired at a warmer sensor temperature, under otherwise identical conditions, as illustrated in Figure 5.

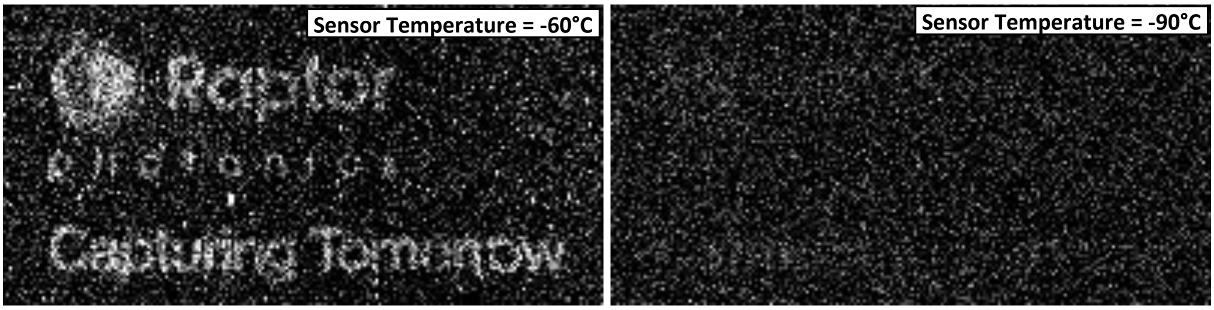

Figure 5: Example 'ghost' images taken at CCD temperatures of -60°C and -90°C using 4 × 4 binning and a readout rate of 75kHz. The shutter was in the closed state throughout the 300 second exposure used for each image.

During this test a single image was acquired at the specified CCD temperature with a maximum signal level approximately equal to the pixel full well capacity. The shutter within the camera was then kept in the closed state for the duration of the 300 second exposure. The 4 × 4 binned images were read out at a pixel rate of 75kHz. The Raptor Photonics name and logo are clearly visible in the image taken at -60°C, whereas at a CCD temperature of -90°C image the ghost image barely visible above the noise floor, illustrating the reduction in residual image signal due to deep cooling the CCD sensor to -90°C.

So, in summary, the main benefits of cooling the CCD sensor to such low temperatures are:

1) **Lower Noise Floor** by minimizing dark signal (and in particular the shot noise component associated with it) we can maximize the sensors photon sensitivity, i.e. weaker signals are discernable above the (lower) noise floor
2) **Reduction of Hot Pixels** enabling more pixels within the array to be used to provide quantitative data, i.e. not saturating in darkness
3) **Increased Dynamic Range** as not only is the noise floor reduced, but also more of the pixel full range can be used to detect 'useful' signal, as opposed to 'unwanted' dark signal. As illustrated in Figure 4, not only does the width of the distribution reduce (consistent with a reduction in the total noise) but the position of the peak moves to lower DN (due to the reduction in dark signal) enabling more of the digitization range to be used for the detection of photons / 'real' signal.
4) **Reduction in Residual Image** as the residual charge is held in the trap sites for a longer period of time. Therefore, for a given exposure period, less charge will be released, hence the amount of residual charge appearing in the final image will be reduced, as illustrated in Figure 5.

Estimation and Minimization of Noise Floor

The total noise, N_{tot} in electrons, of the signal readout from a CCD sensor under specific acquisition conditions is given by:

$$N_{tot} = \left\{ (n_{ps})^2 + (n_{ds})^2 + (n_{rn})^2 \right\}^{1/2}$$

Where n_{ps} is the photon shot noise, n_{ds} is the dark signal shot noise and n_{rn} is the total read noise of the camera system (all in units of electrons). In the absence of photons falling on the sensor, the noise floor, N_{FLOOR}, is given by:

$$N_{FLOOR} = \left[(n_{ds})^2 + (n_{rn})^2 \right]^{1/2}$$

Since the term $(n_{ds})^2$ is effectively the dark signal, DS, this can be re-written as:

$$N_{FLOOR} = \left[(DS) + (n_{rn})^2 \right]^{1/2} = \left[(I_d \times t \times X_{bin} \times Y_{bin}) + (n_{rn})^2 \right]^{1/2}$$

Where I_d is the mean dark current (in electrons/pix/sec), t is the exposure or integration time (in seconds) and X_{bin} and Y_{bin} are the amount of binning applied in X and Y directions respectively (in units of pixels). Note n_{rn} may also increase as X_{bin} and Y_{bin} are increased.

Therefore to achieve the lowest noise floor possible both dark signal and read noise components should be minimized.

Read Noise

The read noise, n_{rn}, is dependent upon a number of factors including the performance of the CCDs' on-chip output amplifier(s), the design and implementation of the camera readout circuitry, the readout rate (i.e. the frequency at which pixel data is being clocked off the sensor) and the amount of on-chip binning applied (in particular the actual implementation of binning by camera hardware and firmware – if this is done incorrectly / poorly the signal to noise ratio with binning applied will not exhibit the expected increase).

Dark Signal

The dark signal also depends upon a number of factors, in particular the temperature of the CCD sensor itself – typically the dark current of a specific device will reduce by a factor of two for every (5 – 7)°C of cooling. However there are many other factors which must also be considered, such as:

1) Pixel size - generally larger area pixels will generate more dark signal per unit time compared to a smaller area pixel at the same temperature.
2) CCD format - e.g. back or front illuminated device, MPP or non-MPP.
3) Sensor manufacturer - including chip design, base materials and fabrication process.
4) Exposure time – defines the period during which dark signal builds up within the pixels.
5) Application of on-chip binning will sum the dark signal within the binned pixels.

How are CCD sensors cooled?

The amount of cooling applied to the sensor is obviously highly dependent upon the particular application – high frame rates generally demand less cooling (as there is little time for dark signal to accumulate before or during readout) – on the other hand long exposures, with slow readout rates and high levels of binning, require the maximum amount of cooling. There are, broadly speaking, four categories of cooling implemented in high performance imaging cameras:

1) Uncooled

The sensor achieves its own equilibrium temperature during operation, without any specifically designed passive / active cooling. Many cameras of this type are simply board-level cameras, which do not require the sensor to be isolated from the ambient conditions.

2) Thermally stabilized at or near the local ambient temperature.

The imaging array can be passively cooled (using air / liquid alone) or actively cooled (using a TEC) to provide a constant sensor temperature either at or close to that of the local environment. Once again, the sensor may not need to be enclosed within a protective housing.

3) ***Moderately cooled (usually to a temperature in the range +10°C to -60°C)***
This range of cooling usually requires the sensor to be enclosed within a protective environment, either dry gas or vacuum. The dew point of the sensor enclosure must be lowered sufficiently in order to prevent formation of condensation / ice on the sensor surface. This is usually achieved by the use of some form of desiccant / getter to remove moisture within the sensor enclosure. The sensor is usually cooled by a TEC and in most cases either a single-stage or two-stage TEC is sufficient for this level of performance.

4) ***Deep cooling (usually to a temperature in the range -60°C to -110°C)***
This level of cooling usually requires generation and maintenance of a vacuum environment around the sensor. This deep cooling can be achieved using liquid nitrogen (LN2) cooling, compressed gas or high-performance, multistage TECs (usually 3 or more stages). TECs provide by far the most compact and user friendly option, and this is the option implemented within Raptor Photonics PentaVac™ Technology. The vacuum has a dual purpose in this case protecting the sensor from damage due to ice formation as well as reducing the heatload applied to the TEC. The internal components and selection of materials used within the vacuum enclosure play a key role, minimizing the heatload presented to the TEC thereby maximizing the sensor cooling achieved. The design implemented in PentaVac™ systems have demonstrated temperature differences in excess of 110°C. At these low temperatures dark currents of a fraction of an electron per pixel per hour have been demonstrated, even on relatively large pixel (13.5μm), back illuminated, MPP devices.

Author Profile

Dr. Geoff Martin is Principal Systems Engineer at Raptor Photonics Ltd, based in Northern Ireland. Raptor is a leading developer of high performance digital cameras using CCD, EMCCD, sCMOS and InGaAs detector arrays. The selection of sensor type, required cooling performance and cooling method can be discussed with Raptor Photonics team to identify the ideal solution for your application.

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